Energetic Particle Transport at Corotating Interaction Regions (CIRs)

Bruce T. Tsurutani[1]
John K. Arballo[1]
Gurbax S. Lakhina[2]

and

Edmond C. Roelof[3]

Erhard Keppler[4]

Jet Propulsion Laboratory[1]
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

Indian Institute of Geomagnetism[2]
Colaba, Mumbai/Bombay
India

Applied Physics Laboratory[3]
Johns Hopkins University
Laurel, MD 20707

Max-Planck Institute für Aeronomie[4]
D3411, Katlenburg-Lindau
Germany

Abstract

We examine energetic particle transport at or near Corotating Interaction Regions (CIRs). The high levels of turbulence at and near the fast forward and reverse shocks bordering the CIR are used to calculate diffusion parallel and perpendicular to the ambient field lines. It is found that the calculated diffusion rates match the energetic ion and electron profiles reasonably well. A significantly lower field variance level at the centers of CIRs and the particle energization sources at the forward and reverse shocks, both naturally lead to a minimum in particle intensity near the stream interface (SI). For one illustrative event, it is found that the SI is not a single tangential discontinuity (TD), but a series of directional discontinuities. Particles can (and do) penetrate the SI boundary in this case.

INTRODUCTION

There has been and continues to be a debate concerning energetic particle transport in interplanetary space. Particles can be pitch angle scattered by interaction with preexisting waves, impeding their particle's propagation parallel to the ambient magnetic field. Particles can also be scattered across magnetic field lines, but perhaps at a much slower rate. Near-ideal events to study concerning parallel and perpendicular particle diffusion are Corotating Interaction Regions (CIRs). At large distances from the Sun, these regions of high magnetic field strength are bounded by fast forward and fast reverse shocks (Smith and Wolf, 1976). Acceleration of energetic particles occur at the shocks (Tsurutani et al., 1982; Kallenrode, 1996; Desai et al., 1998), thus giving well-defined local particle sources. The magnetic fields are quite turbulent within CIRs. Thus particle scattering on field lines within CIRs should be elevated, and parallel and perpendicular diffusion can be examined using both the particle and the wave data simultaneously.

The purpose of this paper is to examine particle transport properties at and near several CIRs. The normalized field variances are calculated to use for pitch angle scattering and for cross-field diffusion estimates. Wave modes have also been identified. Discontinuities have been identified and particle diffusion across them will be commented upon. The modeling predictions will be compared with particle measurements.

B. A "Typical" CIR

Ulysses detected a sequence of 18 CIRs in its passage from the south solar pole to the north solar pole. In our study we have examined the detailed wave and particle features of several of the events and use one for illustration purposes. The properties of other events will be commented on. The Corotating Interaction Region from ~5 UT day 20, 1993 until ~3 UT day 22 is given in Figure 1. The event was detected when Ulysses was at 5.0 AU from the sun at a latitude of $-24°$. The CIR is denoted by compressed magnetic fields and plasma densities, and elevated proton temperatures. The CIR is bounded by a fast forward and reverse shock. The stream interface (SI) is the boundary separating the heated and accelerated slow stream plasma from the heated and decelerated fast stream plasma. The SI for this particular case has been identified by Wimmer-Schweingruber et al. (1997) by ion compositional measurements and is located at ~1230 UT day 20. There are many magnetic discontinuities within the CIR present as well. The detailed properties will be discussed later.

Variance and Discontinuities

The normalized nested magnetic field variances, field components and discontinuity occurrence rates are shown in Figure 2. The field components are in the Solar-Heliosphere (RTN) coordinate system where $\hat{R}$ is radially directed away from the sun, $\hat{T}$ is $\hat{R} \times \hat{\Omega} / |\hat{R} \times \hat{\Omega}|$ where $\hat{\Omega}$ is the rotation axis of the sun, and $\hat{N}$ completes a right hand system. The magnetic field variances have been normalized to unitless quantities so that they can be used to calculate particle pitch angle scattering rates (Kennel and Petschek, 1996; Tsurutani and Lakhina, 1997) and resonant cross-field diffusion rates (Tsurutani and Thorne, 1982). The variances are "nested", i.e., the 10 min, 1 hr and 2 hr normalized variances are shown, with each longer period generally having higher values than the former (this is not absolutely true because the normalization was done over different time averages. The statement is correct for unnormalized nested variances).

Several features can be noted in the normalized variances. The variances are highest near the forward shock (slightly upstream to slightly downstream of the shock) and are high over a broader region near the reverse shock. This double peak in variance values are separated by a region of low field variances. This latter region (of plasma and fields) extends from the SI at ~230 UT day 20 to ~3 UT day 21. This region is characterized by smooth magnetic fields (see the B_T component and $|B|$) and a lack of interplanetary discontinuities (bottom panel).

Two-peaked variance features were noted on the event two rotations prior (days 334-336, 1992), but not for the immediately previous event (day 361-364, 1992). For brevity, the latter event is not shown here. For the day 361-364 event, there was a normalized variance enhancement near the center of the stream and the stream interface. Thus, one notes that there can be a great deal of variability from event-to-event, even though it is the same (but evolved) coronal hole stream source providing the interaction region. Clearly the variable upstream slow solar wind and the evolving coronal hole stream are fundamental to the detailed results of the ensuing interaction.

Energetic Particles

The energetic particles for this CIR are shown in Figure 3. The 61 keV to 20 MeV ions (top four traces) show clear enhancements just upstream of the forward shock. This is in good agreement with previous shock-acceleration observations by Tsurutani et al. (1982), and theoretically discussed by Pesses et al. (1978), Lee (1986) and Decker (1993).

The same particle energies peak have a maximum flux at and near the reverse shock. This latter flux enhancement is generally higher and broader in time (Tsurutani et al., 1982). The lowest HIGHSCALE energy channels (61 - 77 keV, 207 - 336 keV and 0.48 - 0.97 MeV) show a broad peak from ~4 UT day 21 to ~03 UT day 22, whereas the higher energy ions (1.2 - 2.0 MeV and 8-19 MeV) and the energetic electrons (38 - 315 keV) have definite peaks primarily at the reverse shock. The fluxes decrease with increasing distance from the shock.

The region of the broad low energy ion enhancement inside the reverse shock corresponds reasonably well to the region of high normalized field variances. Is it possible that cross-field diffusion can explain this feature? Later, we will estimate cross-field diffusion rates, to examine the possibility of this particular point. It should be noted that this region of the CIR has field lines that cross the shock closer to the sun (see Figure 4). Thus another possibility is that these particles were generated earlier in time (by shock acceleration) and then propagated to the spacecraft by diffusion parallel to the magnetic field rather than across it.

The energetic electron profile is different than either the low energy ion or high energy ion profiles. There is only one particle maximum and that is at the reverse shock. The peak flux occurs at the reverse shock and falls off slowly in the sunward direction (tens of days). The falloff is more rapid in the antisunward direction (~day). The flux decrease within the CIR (antisunward direction) is smooth and shows little effects due to the low variance (smooth field) region, to the SI, or to the forward shock. There is only a slight electron flux enhancement at the SI. These features will also be explored in the wave-particle interaction section.

The discontinuity occurrence rate variations (shown for each 6 hr interval) are similar to the variations in the nested normalized variances. The largest occurrence rates are at and near the reverse shock. There is an enhancement in occurrence rate at the forward shock and a decrease (to zero) in the high, smooth-field region discussed previously. This profile is not unexpected, based on previous work. Tsurutani et al (1994), Smith et al. (1995), and Balogh et al. (1995) have shown that nonlinear Alfvén waves are a dominant feature of the high-speed solar wind streams, and Tsurutani et al. (1996; 1997) have shown that nonlinear Alfvén waves are often phase-steepened, with rotational discontinuities (RDs) at their edges. Thus, since the CIR contains compressed Alfvénic fluctuations just downstream of the forward shock and upstream of the reverse shock (Tsurutani et al., 1995), one could expect an increase in the number of discontinuities as well. Of course there could be other wave modes and discontinuities generated by the solar wind interaction with the two shocks. At this time one cannot rule out significant contributions from this latter mechanism.

Wave Modes

To determine the wave modes present within and just upstream and downsteam of the CIR, we use the highest time resolution magnetic field data available. This is 2s, for the Ulysses mission (Balogh et al. 1989). Unfortunately, the plasma instrument cadence is too low to use for additional wave information. Thus, all analyses will be performed using the magnetic field alone. Minimum variance analyses are used to determine magnetic wave polarizations (Smith and Tsurutani, 1976).

About 25 short intervals were selected for detailed, high resolution examinations of wave polarizations and waveforms. Intervals upstream, within, and downstream of the CIR were examined. Within the CIR, three dominant types of modes are detected: arc-polarized, slightly compressive waves, mirror-mode structures and turbulence. We will give examples of each.

Figure 5 illustrates a wave interval (between the vertical dashed lines) on day 21, 1993 in minimum variance coordinates (Sonnerup and Cahill, 1967; Smith and Tsurutani, 1976). B_1, B_2 and B_3 correspond to the field components in the maximum, intermediate and minimum variance coordinate system, respectively. The minimum variance direction is (0.85, 0.41, 0.33) in the

RTN coordinate system. Figure 5 shows that most of the field perturbation occurs in the B_1 component. B_3 is approximately zero. The field magnitude is relatively steady in this event.

The B_1 - B_2 hodogram is at the bottom. The wave is seen to be arc-polarized, where the beginning (1) and end (2) are clearly denoted. This is the typical case within this CIR. $\theta_{B_3B_O} \approx 86°$. Similarly results were found and presented in Tsurutani et al. (1992).

Figure 6 is an example of "turbulence" within the CIR. This occurs on day 20 from 2129:00 to 2229:40 UT. The field magnitude has a slight decrease throughout the interval. The B_1 - B_2 hodogram is again at the bottom. It appears as if this "scatter" in the hodogram could be due to a number of small linear/arc-polarized waves.

Figures 7 shows the wave analyses for a magnetic hole. The "polarization" is characteristically linear. Note that there are several field magnitude decreases or magnetic (Turner et al., 1977; Winterhalter et al., 1995; Ho et al., 1995) in the Figure. More can be noted in the trailing portion of the CIR shown in Figure 1. Ho et al. (1995) have shown that many of these structures could be generated by the mirror mode instability where:

$$\beta_\perp / \beta_\parallel > 1 + \frac{1}{\beta_\perp} \tag{1}$$

In the above inequality, β is the plasma beta, which is equal to $\sum_i 8\pi N_i k T_i / B_o^{\,2}$.

In the above expression, N is the plasma density, T_i is the ion temperature and k is the Boltzmann constant. The magnetic field characteristics of mirror mode structures are changes (during this study) primarily in field magnitude and little or no change in direction. β within these structures are >1. At times β can be well over 100.

Discontinuities

The directional discontinuities (DDs) are selected using a computerized method applied to 1-min average vectors. A description of the criteria can be found in Tsurutani and Smith (1979). Once discontinuities are identified, high-time resolution analyses are used to determine the normal direction, the magnetic field component along the normal (B_N), and the larger field magnitude on either side of the discontinuity (B_L). With these parameters, we use the Smith (1973a, b) method to identify whether the discontinuities are tangential or rotational in nature.

The most interesting discontinuities are the ones at the "stream interface" shown in Figure 8. Wimmer-Schweingruber et al. (1997) has indicated an ion compositional change at ~1230 UT. From ~1220 to ~1250 UT, there is a large-scale field directional rotation in the B_I component. However in the field magnitude plot, one can note six prominent field decreases and increases (discontinuities). These are labeled in the Figure. Each of the six events have been analyzed using the minimum variance technique.

Many of the discontinuities have complex properties. Event 1 has a normal orientation 13° relative to the magnetic field. $\Delta|B|/B_L = 0.06$ and $B_N/B_L = 0.97$ placing it as a rotational discontinuity. However, it is a little unusual in that there is a distinct magnetic field magnitude change across the structure. The second event at 1223 UT is a discontinuity that has both RD and TD properties. B_N/B_L - 0.17 and $\Delta|B|/B_L = 0.06$. There is little or no field rotation across this discontinuity. It would not have been selected as a DD event by the TS method. Event 3 was selected as the interval 1224:10 to 1229:50 UT. Thus, some of the slow field rotation plus the sharp field decrease is included. Analysis of this interval gives us a nice rotational discontinuity with a significant magnitude change: $B_N/B_L = 0.69$ and $\Delta|B|B_L = 0.10$. For event 4, the interval 1230 to 1238 UT was analyzed. The results are shown in Figure 9. This discontinuity is located in the center of the large scale rotation. This discontinuity has the properties of both a RD and a TD. $B_N/B_L = 0.02$ and $\Delta|B|/B_L = 0.1$. $\theta_{kB} = 89°$. Event 5 would again be classified as having RD and TD properties. B_N/B_L - 0.13, $\Delta|B|/B_L = 0.07$. $\theta_{kB} = 82°$. Finally, event 6 is similar to event 5, having both RD and TD properties. $B_N/B_L = 0.1$, $\Delta|B|/B_L =$ 0.08 and $\theta_{kB} = 85°$.

The nature of these discontinuities and the role that they play in the SI are not possible to probe further at this time. High time resolution plasma data are necessary, which unfortunately is not available. For example the pair of events and interval in-between discontinuities 5 and 6 may be a mirror mode structure. Examination of the instability criteria could help confirm this.

Reconnection could be occurring across the broad field rotation area. Evidence of plasma jetting and heating could tell us if this is occurring or not. The presence of such microstructure within the large field rotation is indicating that for this case, there is not a simple TD bounding the two different plasmas. The large scale field indicates this as well. This result has important implications for energetic particle transport. There is no clear large scale tangential discontinuity at the center of the CIR to impede particle flow within the CIR. This particular interface may be thought of as consisting of a number of small scale RD structures.

C. Wave-Particle Interactions.

Resonant interactions with the magnetic component of electromagnetic waves is the dominant mechanism for scattering energetic ions and electrons in interplanetary space. From Kennel and Petschek (1966) we have:

$$D^{\pm}_{\alpha\alpha} = \left(\frac{B_\omega}{B_o}\right)^2 \Omega^{\pm}_g \eta \tag{1}$$

where B_ω is the wave amplitude, B_O the field magnitude and $\Omega^{\pm}_g$ are particle gyrofrequencies, and η is the fractional amount of time the particles are in resonance with the waves. $D^{\pm}_{\alpha\alpha}$ is the pitch angle diffusion.

The quantity $(B_\omega/B_O)^2$ was calculated earlier and was shown as the nested normalized variances. To determine the resonant wave power, one must determine the frequency from the cyclotron resonant condition:

$$\omega - k_{\|} V_{\|} = n\Omega^{\pm}_g \tag{2}$$

when ω is the wave frequency, $k_{\|}$ and $V_{\|}$ are the parallel components of the wave vector $\vec{k}$ and particle velocity vector $\vec{V}$, respectively, $n = 0, \pm 1, \pm 2$ is the harmonic number. One can make a first-order simplification by assuming the waves are propagating parallel to $\vec{B}$. For the normal first-order cyclotron resonance, one gets:

$$\omega/k - V^{\pm}_R = \Omega^{\pm}_g / k \tag{3a}$$

for both ions (+) and electrons (–), and $V^{\pm}_R$ stands for the resonant velocity of the particle.

This can be further compressed to:

$$V_{ph} - V_R^{\pm} = \frac{\Omega_g^{\pm}}{\omega} V_{ph} \quad (4)$$

where V_{ph} is the Alfvén speed for the low frequency waves. V_{ph} is ~50 - 70 km s^{-1} in the solar wind at Ulysses distances from the sun.

The cross-field diffusion rate, $D_\perp^{\pm}$, due to resonant-wave particle interactions have been derived by Tsurutani and Thorne (1982). Assuming a diffusion rate much less than the Bohm rate for the magnetic component of the waves, one has:

$$D_\perp^{\pm} \approx 2\left(B_\omega / B_L\right)^2 D_{max} \quad (5)$$

where $D_{max} = E_\perp c / 2eB_o$, the Bohm rate. $E_\perp$ is the perpendicular particle kinetic energy, c the speed of light, and e the electronic charge. At the maximum, or Bohm rate, the particles diffuse a gyroradius in distance every cyclotron period.

Pitch Angle Scattering Rate

To illustrate some of the results, we perform scattering rate calculations for only a few representative energies: 100 keV protons, 10 MeV protons and 100 keV electrons. We first do the calculations near the reverse shock inside the CIR. From Figure 2, the average field magnitude is ~2 nT. Thus $\Omega_g^+ \approx 2 \times 10^{-1}$ rad s^{-1} and $\Omega_g^- \sim 4 \times 10^2$ rad s^{-1}. Assuming an Alfvénic phase velocity of 50 km s^{-1} and $V_A / V_{sw} \approx 10^{-1}$ (the wave frequency in the plasma frame has been Doppler shifted upward by a factor of 10). The wave power at resonance is calculated.

100 keV Protons

From the resonance condition, we find that these particles will cyclotron resonate with 50 min period waves. Examining Figure 2, we find $\sigma^2/B_O^2|_{4min} \sim 10^{-2}$. From equation (1) we find $T_{scattering}$ ~ 500s. The gyroperiod is ~30s. Thus these energy particles are on weak pitch angle diffusion.

It seems quite possible that these particles are shock accelerated ions that have propagated along magnetic field lines into the CIR as illustrated in Figure 4.

The cross-field diffusion rate is ~2×10^{-2} D_{max} or 2.0% of the Bohm diffusion rate. The particles at these energies have access to neighboring magnetic field lines, but the diffusion is at relatively slow rates. Thus the cross-field diffusion rare is an order of magnitude slower than diffusion in the parallel direction.

1 MeV protons

For these energy particles, resonance occurs with 150 min period waves. From Figure 2, $(\sigma_w^2/B_O^2)|_{50s} \sim 3 \times 10^{-2}$. The pitch angle scattering time is ~170s, thus these particles are on near-strong pitch angle diffusion. This high energy tail could derive from energy extracted from the waves. The cross-field diffusion rate is ~ 0.06 D_{Bohm}, higher by a factor of 3 times than for 100 keV protons.

100 keV Electrons

100 keV electrons cyclotron resonate with 50s period waves. The resonant wave power in the plasma rest frame is $\sigma_w^2/B_O^2|_{60S} \sim 3 \times 10^{-3}$, leading to a diffusion rate equal to ~1.0. The electrons are on strong diffusion. The cross-field diffusion rate is 0.006 D_{max} at the Bohm rate means the particles travel 6×10^{-3} gyroradii in one cyclotron period. For a 2 nT field, the 100 keV electron gyroradii is 530 km. The cross-field diffusion rate is ~10^5 km^2 s^{-1}. The electrons thus have very rapid access to neighboring field lines.

100 keV Protons at Variance Minimum

The resonant wave power at the center of the CIR is $\sigma_w^2 / B_O^2 = 3 \times 10^{-4}$. The cross-field diffusion rate is 6×10^{-4} D_{max}. The diffusion rate is almost two orders of magnitude less in this region of space.

SUMMARY AND CONCLUSIONS

By measuring the normalized field variances and using the normalized wave power at the particle resonant frequencies, parallel and perpendicular particle diffusion can be directly calculated. It is shown that near the reverse shock, the wave power is considerably higher leading to both more rapid pitch angle diffusion and cross-field diffusion. The ratio of the two quantities is approximately 10:1, by a value that has been estimated from particle measurements.

The diffusion rates are higher for higher energy particles. The example shown was 1 MeV protons in contrast to 100 keV. This can be understood from equation (4). The resonant frequency decreases directly with particle speed. Because of the power-law type spectrum of the waves, the wave power is greater for more energetic particles.

Electrons are most rapidly scattered. For the waves measured, these particles are on strong diffusion and may be energized directly by wave-particle interactions. There is no specific need to invoke shock interactions. The cross-field diffusion rate is comparable to half the solar wind speed, so the particles have rapid access to neighboring magnetic field lines.

The low field variance region near the center of the CIR leads to a reduction in cross-field diffusion of ions and electrons by several orders of magnitude. This is noted in all energetic particle data as a rapid falloff of the fluxes from the reverse shock towards fields more in the sunward direction.

Acknowledgments: Portions of this work were performed at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, under contract with the National Aeronautics and Space Administration. We thank E. Roelof and E. Keppler for useful discussions concerning the energetic particle features.

REFERENCES

Balogh, A., E.J. Smith, B.T. Tsurutani, D.J. Southwood, R.J. Forsyth and T.S. Horbury, The heliospheric magnetic field over the south polar region of the sun, *Science, 268*, 945, 1995.

Decker, R.B., The role of magnetic loops in particle acceleration at nearly perpendicular shocks, *J. Geophys. Res.,* **98**, 33, 1993.

Desai, M.I., R.G. Marsden, T.R. Sanderson, A. Balogh, R.J. Forsyth and J.T. Gosling, particle acceleration at corotating interaction regions in the three-dimensional heliosphere, J. *Geophys. Res.*, **103**, 2003, 1998.

Ho, C.M., B. T. Tsurutani, B.E. Goldstein, J.L. Phillips and A. Balogh, Tangential discontinuities at high heliographic latitudes (~ −80°), *Geophys. Res. Lett.,* **22**, 3409, 1995.

Kallenrode, M.-B., The temporal and spatial development of MeV proton acceleration at interplanetary shocks, *J. Geophys. Res.*, **102**, 22347, 1997.

Kennel, C.F. and H.E. Petschek, Limits on stably trapped particle fluxes, *J. Geophys. Res.,* **71**, 1, 1966.

Lee, M.A., Acceleration of energetic particles at solar wind shocks, *in The Sun and the Heliosphere in Three Dimensions*, edited by R.G. Marsden, Reidel, Hingham, Mass., 305, 1986.

Pesses, M.E., J.A. Van Allen and C.K. Goertz, Energetic protons associated with interplanetary active regions 1-5 AU from the Sun, *J. Geophys. Res.,* **83**, 553, 1978.

Smith, E.J., A. Balogh, M. Neugebauer, and D. McComas, Ulysses observations of Alfvén waves in the southern and northern hemispheres, *Geophys. Res. Letts.,* **22**, 3381, 1995.

Smith, E.J., Identification of interplanetary tangential and rotational discontinuities, *J. Geophys. Res.,* **78**, 2054, 1973a.

Smith, E.J., Observed properties of interplanetary rotational discontinuities, *J. Geophys. Res.,* **78**, 2088, 1973b.

Smith, E.J. and B.T. Tsurutani, Magnetosheath lion roars, *J. Geophys. Res.,* **81**, 2261, 1976.

Smith, E.J. and J.H. Wolf, Observations of interaction regions and corotating shocks between one and five AU: Pioneers 10 and 11, *Geophys. Res. Lett.,* **3**, 137, 1976.

Sonnerup, B.U.O. and L.J. Cahill, Jr., Magnetopause structure and altitude from Explorer 12 observatory, *J. Geophys. Res.,* **72,** 171, 1967.

Tsurutani, B.T. and E.J. Smith, Interplanetary discontinuities: Temporal variations and the radial gradient from 1 to 8.5 AU, *J. Geophys. Res.,* **84**, 2773, 1979.

Tsurutani, B.T., E.J. Smith, K.R. Pyle and J.A. Simpson, Energetic protons accelerated at corotating shocks: Pioneer 10 and 11 observations from 1 to 6 AU, *J. Geophys. Res.*, **87**, 7389, 1982.

Tsurutani, B.T. and R.M. Thorne, Diffusion processes in the magnetopause boundary layer, *Geophys. Res. Lett.*, **9**, 1247, 1982.

Tsurutani, B.T., D.J. Southwood, E.J. Smith, and A. Balogh, Nonlinear magnetosonic waves and mirror mode structures in the March 1991 Ulysses interplanetary event, *Geophys. Res. Lett.*, **19**, 1267, 1992.

Tsurutani, B.T., C.M. Ho, E.J. Smith, M. Neugebauer, B.E. Goldstein, J.S. Mok, J.K. Arballo, A. Balogh, D.J. Southwood and W. C. Feldman, The relationship between interplanetary discontinuities and Alfvén waves: Ulysses observations, *Geophys. Res. Lett.*, **21**, 2267, 1994.

Tsurutani, B.T., C.M. Ho, J.K. Arballo, B.E. Goldstein, Large amplitude IMF fluctuations in corotating interaction regions: Ulysses at midlatitudes *Geophys. Res. Lett.*, **22**, 3397, 1995.

Tsurutani, B.T., C.M. Ho, J.K. Arballo, E.J. Smith, B.E. Goldstein, M. Neugebauer, A. Balogh, and W.C. Feldman, Interplanetary discontinuities and Alfvén waves at high heliographic latitudes: Ulysses, *J. Geophys. Res.*, **101**, 11027, 1996.

Tsurutani, B.T., C.M. Ho, J.K. Arballo, G.S. Lakhina, K.-H. Glassmeier and F.M. Neubauer, Nonlinear electromagnetic waves and spherical arc-polarized waves in space plasmas, *Plasma Phys. Controlled Fusion*, **39**, A237, 1997a.

Tsurutani, B.T. and G.S. Lakhina, Some basic concepts of wave-particle interactions in collisionless plasmas, *Rev. Geophysics*, **35**, 491, 1997.

Turner, J.M., L.F. Burlaga, N.F. Ness, and J.F. Lemaire, Magnetic holes in the solar wind, *J. Geophys. Res.*, **82**, 1921, 1977.

Wimmer-Schweingruber, R.F., R. von Steiger and R. Paerli, Solar wind stream interfaces in corotating interaction regions: SWICS/Ulysses results, *J. Geophys. Res.*, **102**, 17407, 1997.

Winterhalter, D., M. Neugebauer, B.E. Goldstein, E.J. Smith, B.T. Tsurutani, S.J. Bame and A. Balogh, Magnetic holes in the solar wind and their relation to mirror-mode structures, *Space Sci. Rev.*, Kluwer, Netherlands, **72**, 201, 1995.

Figure Captions

Figure 1. The plasma magnetic field magnitude characteristics of a representative CIR. The stream interface (SI) occurs at ~1230 UT day 20.

Figure 2. The normalized magnetic field variances for the CIR in Figure 1 in RTN coordinate (top four panels), the field components (next four panels), and the number of discontinuities per day (bottom). The legend for 10 min, 30 min, 1-hr. and 2-hr. variances is given on the right.

Figure 3. HIGHSCALE energetic ions (top panel) and energetic electrons (middle panel).

Figure 4. A schematic of magnetic field lines associated with a CIR.

Figure 5. An example of a wave within the CIR.

Figure 6. Same as Figure 5, but with multiple linearly polarized waves.

Figure 7. An example of mirror mode structures within the CIR.

Figure 8. Complex field structure composing the stream interface.

Figure 9. An analyses of discontinuity 5 in Figure 8.